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Landfill mining as a strategic tool towards global sustainable development

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ABSTRACT

Paris Agreement, signed in 2015 by 195 countries around the world as a measure to stop and reverse the consequences of global warming and promote Sustainable Development (SD), sets out strategies for reducing greenhouse gases and the Agenda 2030, which contains the 17 Sustainable Development Goals (SDGs). The participating countries of these agreements are demanded to develop public policies that incorporate the signed commitments. Regarding this issue, a topic of great importance is solid waste management. To decrease the generation of waste through prevention, reduction, recycling, and reuse become fundamental. Landfill Mining (LM) is presented as a strategic tool that, if established properly within waste management public policies, it can contribute to SD and mitigation of climate change. This article reviews more than a hundred projects carried out in North America, Europe, Asia and the Middle East, which were cataloged according to the objectives they attended. Economic, social and environmental benefits and their relations with the compliance of SDGs are discussed.

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1. Introduction

The concept of Sustainable Development (SD) was presented by the Brundtland Report in the Nations General Assembly in 1987 and became popular worldwide. This concept "*involves increases in the quality of life which are inter- and intragenerationally equitable*" (Qizilbash, 2001, p. 135), through a process of changes and community participation, with social, economic and environmental aspects as pillars. The need for integrating these pillars led to the consolidation of the concept over the years, culminating in important debates and the establishment of agreements between countries, whose objectives are to achieve their SD. In 2015, in order to counteract climate change, the Paris Agreement was signed and shall be implemented from 2020 onwards. In addition, in the same year, the World Sustainable Development Summit approved the Agenda 2030 that contains the 17 Sustainable Developments Goals (SDGs) (UN, 2015a). Gomez-Echeverri (2018) affirms that Agenda 2030 goals "*aspire to transform the way in which development issues and climate change are addressed*" (p. 1).

One of the areas that deserved special attention of the participating countries, because of its association with environmental and social issues, is the solid waste management. Inadequate final disposal of waste is one of the challenges for achieving SD around the world. Among its repercussions there are the contamination of terrestrial and aquatic ecosystems, the depletion of natural resources, the poor quality of living conditions in the surroundings, the public health problems, and climate change (ISWA, 2016). Moreover, the contamination caused by improperly closed landfills continues even after several decades of disuse (Reinhart, 1993). A decrease in solid waste generation through prevention, reduction, reuse, and recycling is essential in order to comply with SDGs (Lombardi, 2016). In this context, Landfill Mining (LM) is presented here as a strategic alternative for SD and proper waste management. This practice can return the materials to the productive cycle and it also can bring other social, economic and environmental benefits.

LM can be a tool to potentiate the fulfillment of the objectives outlined in these global agreements in a different way. Considering that final disposal in landfills is the most popular option in many countries due to relative low costs involved, despite controversies regarding its installation (Hoornweg and Bhada-Tata, 2012). LM

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allows the reduction of the associated environmental impacts and it extends the landfills useful life (Joseph et al., 2004; Krook et al., 2012).

One of its benefits is the recovery of valuable waste such as metals, including rare-earth elements, which contribute to economic growth and the development of green technologies (Mikhaylov, 2010 and EC, 2014; Burlakovs et al., 2018). Moreover, this technique helps to reduce greenhouse gas emissions from landfills and dumpsites, by the organic compound's treatment and recovery (Weng et al., 2015).

The aim of this article is to discuss the role of the LM for the fulfillment of several SDGs. It should be noticed that the LM brings other economic, social and environmental benefits, which will be presented throughout this article, demonstrating that as a strategic tool for waste management public policies can promote greater efficiency in the direction of SD.

2. Material and methods

From the study of Landfill Mining, also known as Landfill Reclamation, implementation worldwide, the authors sought to verify its influence in the field of sustainability. The strategy used was to classify the purposes with which LM was implemented in different regions of the world and analyze how the benefits of LM promote compliance with SDGs.

For this purpose, data were collected from scientific publications and reports from private sector. The article considers 112 LM projects (including pilot projects) executed in 21 countries worldwide since 1953. The information was organized by presenting the objectives of each of these projects. The classification of these objectives was adapted from the study conducted by Ortner et al. (2014), who categorized the objectives from 60 projects worldwide. In the present article, these categories were adapted and then used to categorize the projects. The used categories are: environmental protection, recovery of excavated waste, extension of useful life, studies, waste characterization, urbanization, closure and post-closure (See Table 1).

After the classification of these projects according to the adapted categories and their location, a brief description of motivations and conjuncture of each region to undertake this type of projects were made. This description sought to clarify how this tool promotes the solution of different problems and to discuss the governmental role for the promotion of these projects in each region.

The analysis of the data was carried out in the following manner: firstly, the percentage frequency distribution of the objectives worldwide and for every region was conducted. For some projects, the objective was to recover excavated waste, and, in the table, this category was divided into three different applications; however, when calculating the percentage frequency distribution, it was counted unitarily. Therefore, in case of presenting more than one type of waste recovery, it will only be counted once. Secondly, according to the research objective the objectives' categories that were more relevant were selected. Finally, the benefits of each of these categories were correlated with the SDGs (and its specific targets), evaluating their impact on compliance with this international agreement. That way the strategic value of this tool was demonstrated.

3. Results

Table 2 shows the LM projects evaluated throughout this research. This table also presents the objectives categories for each project. The projects were organized according to the city, country and the region where they were carried out. The analysis of each region is presented below to clarify how this tool supports the solution of different problems and to know the governmental task for the promotion of these projects.

3.1. Middle East

The landfill of Tel Aviv in Israel was the first known worldwide initiative and aimed to obtain material to produce fertilizers for orchards. Ferrous and other recyclable metals were also recovered (Von Stein and Savage, 1993). This was the only LM project worldwide reported until the 1980s. The other projects in the Middle East were in United Arab Emirates (UAE) and Lebanon.

The project executed in UAE was at Sharjah city in the emirate of the same name, which is the third largest emirate of this country. The landfill was built about 12 km far from the city center, but with the city growth, enclosing and urbanizing its surroundings began (Goeschl, 2006). The project was divided into 4 stages, carried out between 2004 and 2008, in which 1.9 million square meters were excavated (Goeschl, 2010). The first stage was the characterization of the waste, gases and leachate. In the second one, the biological treatment of aerobization was used to stop the anaerobic processes, and then to absorb the gases and the injected air mixture then cleaning through biofilters (Goeschl, 2006). The third and fourth stages were the excavation and treatment of the recovered material, respectively (Goeschl, 2010). As part of the project, an almost

Table 1
Details of the categories used to evaluate the Landfill Mining projects' objectives.

Categories	Description
Environmental Protection	Groundwater protection, risk mitigation for surface water, groundwater and air (landfill emissions), landfill stability, extraction of hazardous waste, reclaiming, landfill rehabilitation, biological treatment for stabilization of organic matter.
Closure and post-closure	Reduction of post-closure care
Lifetime extension	Reduction of refilled waste volume, reuse of land as landfill under favorable environmental conditions
Recovery of excavated waste	1. Soil recovery 2. Energy Recovery 3. Recyclable materials recovery
Waste characterization	Waste characterization
Urbanization	Demand for land for urban development plan or industry use, construction of housing, industry or recreation projects (parks), planted vegetation.
Studies	Pilot studies and demonstration projects Landfill reclamation procedures Materials recovery feasibility Technical and economic feasibility studies Design parameters and infrastructure Technological routes for recovery of excavated waste

Adapted from Ortner et al. (2014).

Table 2
Landfill mining projects executed in the Middle East, Asia, North America and Europe.

Country	Project area	Types of waste	Period	Objectives									References
				Environmental Protection	Closure and post-closure	Lifetime extension	Recovery			Waste characterization	Urbanization	Studies	
							Soil	Energy	Recyclable materials				
Middle East													
Israel	Tel Aviv Dumpsite	Mainly MSW	1953				X		X				Savage et al. (1993)
United Arab Emirates	Sharjah Dumpsite	Mixed Waste (MSW, industrial and hazardous waste, C&D, sludge)	2004–2007	X			X		X	X	X		Goeschl (2006)
Lebanon	Normandy Dumpsite, Beirut	Mixed Waste (MSW, C&D, weapons)	2003–2005	X			X	X			X		Lechtenberg (2008); North and South (2013)
	Saida Dumpsite	Mixed waste (MSW, C&D and hazardous waste)	2013–2015	X			X				X		Gharib (2017); UNDP, 2018
Asia													
India	Deonar Dumpsite	Mainly MSW	1989				X			X			Scheu and Bhattacharyya (1997); Joseph et al. (2004)
	Yusufguda Dumpsite, Hyd	Mainly MSW	1997–1998								X		Patel (2016)
	Kodungaiyur Dumpsite, Chennai	Mainly MSW	2001–2004							X		X	Hogland and Joseph (2008); Joseph et al. (2003)
	Perungudi Dumpsite, Chennai	Mainly MSW	2001–2004							X		X	Hogland and Joseph (2008); Joseph et al. (2003)
	Pune Dumpsite	Mainly MSW	2002	X		X	X						Hogland and Joseph (2008); Joseph et al. (2003)
	Panchvati Dumpsite, Nasik	Mainly MSW	2002–2003	X					X		X		Patel (2016)
	Avaniapuram Dumpsite, Madurai	Mainly MSW	2003–2004	X									Patel (2016)
	Gorai Dumpsite, Mumbai	Mainly MSW	2003–2004	X		X							Patel (2016)
	Autonagar Dumpsite, Hyderabad	Mainly MSW	2003–2004 2007	X			X						Nekkanti and Kumar, 2018; Patel (2016)
	Ajmer Dumpsite, Rajhastan	Mainly MSW	Since 2007	X				X					Ford et al. (2013); Lechtenberg (2008)
	Faridabad Dumpsite	Mainly MSW	2008–2009								X		Patel (2016)
	Ghazipur Dumpsite, East Delhi[a]	Mixed waste (MSW, C&D, drain silt; poultry and non-hazardous hospital waste)	2013	X				X				X	USEPA and CCAC, 2017; Ranjan et al. (2014)
China	San Lin Transfer Site	Mainly MSW	1997				X	X				X	Howlett (1997); Joseph et al. (2004)
Taiwan	Neihu landfill, Taipei	Mainly MSW	2006–2013	X			X	X			X		Weng et al. (2015)
	Shanchuku Sanitary landfill, Taipei	Mixed waste (MSW, C&D)	2013	X			X				X		AECOM, 2015; Betasolo et al. (2017)
South Korea	Nanjido, Seoul	Mixed waste (MSW, C&D, Industrial Waste)	1998–2020	X			X				X		Rosendal (2009); SUSA, 2016; Twyford (2008); Underwood and Yoon (2017)
	Ulsan Dumpsite[a]	Mainly MSW	–				X					X	Cha et al. (1997)
Sri Lanka	Guhagoda[a]	–	2002–2005			X	X					X	Werellagama and Samarakoon (2007)
Pakistán	Fauji Dumpsite	Mainly MSW	2007–2008	X				X					Lechtenberg (2008)
Tailandia	Nong Khaem Dumpsite, Bangkok	Mainly MSW	–									X	Strange (2010)
	Nonthaburi	Mixed waste (MSW, hazardous waste)	–							X		X	Prechthai et al. (2006)

	Maung Pathum Dumpsite, Pathumthani province	Mainly MSW	–							X		X	Hogland and Joseph (2008)
North America													
United States of America	Naples Landfill in Collier County, Florida[b]	MSW	1986–1992	X		X		X	X		X	X	IWCS, 2009; Von Stein and Savage, 1993; Joseph et al. (2004); USEPA, 1997
	Thompson landfill, Connecticut	MSW	1988					X					Burlakovs et al. (2017); Guerriero (1996); Joseph et al., 2004 (Nelson, 1995)
	Winnebago County Landfill, Wisconsin	Mainly MSW	1990	X					X				IWCS (2009)
	Edinburg landfill, New York	MSW	1990–1991 [1st] 1992 [2nd]	X		X			X			X	Guerriero (1996); IWCS, 2009; Strange (2010); USEPA, 1997
	Chester, New York	MSW	–									X	Guerriero (1996)
	Colonie, New York	MSW	–									X	Guerriero (1996)
	Horicon, New York	MSW	–									X	Guerriero (1996)
	Moriah, New York	MSW	–									X	Guerriero (1996)
	Tonawanda, New York	MSW	–									X	Guerriero (1996)
	Phoenix Rio Salado Project (two landfills and various dumpsites), Arizona	Mixed waste (MSW, C&D, tires, hazardous waste)	1990–2012	X					X		X		Dhar (2015); IWCS, 2009
	Bethlehem landfill, New Hampshire	MSW	1991					X					Joseph et al. (2004); Nelson (1995)
	Frey Farm landfill, Lancaster, Pennsylvania	MSW	1991–1996					X	X	X			Joseph et al. (2004); USEPA, 1997
	Martone landfill, Barre, Massachusetts	MSW	–					X	X				CIWMB (1993); Rosendal (2009); Joseph et al. (2004)
	Nashville Ash Monofill, Tennessee	incineration ashes	1993					X		X	X		Arcaini (2000); Nelson (1995)
	Newbury landfill, Massachusetts	MSW	1993					X	X		X		Nelson (1995)
	Hague landfill, New York	MSW	1993 [pilot] 1994			X			X			X	Guerriero (1996); Nelson (1995); Steuteville (1996); Joseph et al. (2004)
	Bethlehem landfill, Pennsylvania	MSW	–	X				X	X				Nelson (1995)
	Halifax, Vermont	MSW	1995	X									Ford et al. (2013); Reeves and Murray (1996)
	Pike Sanitation Landfill, Ohio	MSW	1996–2000	X									IWCS (2009)
	Dean Forest landfill, City of Savanna, Georgia	Mixed waste (incineration ashes, MSW, C&D, sludge)	1997–2006	X				X					IWCS (2009)
	Live Oak landfill, Atlanta, Georgia	MSW	1997 [pilot] 1997–1998								X	X	Joseph et al. (2004)
	Clovis Landfill, California	MSW	1998–2008	X				X	X				IWCS (2009)
	Wyandot County Landfill, Ohio	MSW	1999	X									IWCS (2009)
	Central Disposal Systems Landfill, Lake Mills, Iowa	MSW	2000	X				X	X				IWCS (2009)
	Shawano County Landfill, Wisconsin	MSW	2001–2002	X					X				IWCS (2009)
		MSW	2005–2008	X				X					IWCS (2009)

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Table 2 (*continued*)

Country	Project area	Types of waste	Period	Objectives								References
				Environmental Protection	Closure and post-closure	Lifetime extension	Recovery			Waste characterization	Urbanization	Studies	
							Soil	Energy	Recyclable materials				
	La Crosse County, Wisconsin												
	Perdido landfill, Escambia County, Florida	Mixed waste (MSW, tires)	2008 [pilot] 2009–2011	X		X	X					X	Dhar (2015); IWCS, 2009; Jennings et al. (2010)
	Ecomaine landfill/ashfill, Maine	MSW incinerator ashes	2011–2015						X			X	Wagner and Raymond (2015)
Canada	McDougal, Ontario	–	1994	X		X							Nelson (1995)
	Barrie landfill, Ontario	Mixed Waste (MSW, C&D, tires)	2008 [pilot] 2009–2015	X		X	X					X	Dewaele and Brunet (2016)
Europe													
United Kingdom	Old dockyard tip at Chatham dockyard estate	Mainly waste shipbuilding	1980s	X							X		Atkinson (2010); Ford et al. (2013)
	Packington landfill, Birmingham	Mixed waste (MSW, C&D, hazardous waste)	–	X									Hayward-Higham (2008)
	Whinney Hill landfill, Lancashire	–	–	X									Hayward-Higham (2008)
	Jameson Road, Lancashire	–	–	X									Hayward-Higham (2008)
	Two council landfills, Kent	MSW	2000								X		Ford et al. (2013)
	Sussex Dumpsite	Mainly MSW	–	X							X		Ford et al. (2013)
Austria	Donaupark Landfill, Vienna	Mixed waste (MSW, C&D)	1990–1991	X					X				Dorrie et al. (2009); Spillmann (2001)
	Helene Berger, Vienna Neustadt	Mixed waste (MSW, C&D, industrial and hazardous waste)	1996–1999	X			X	X					Dorrie et al. (2009); Spillmann (2001)
	Kiener-Deponie	Mixed waste (MSW and special waste)	2001	X									EC, 1998; Federal Environmental Agency Austria (2010); Ortner et al. (2014)
	Fischer	Mixed waste (MSW, industrial and hazardous waste)	2002–2006	X									Dorrie et al. (2009); Federal Environmental Agency Austria (2010); Ortner et al. (2014)
	Halbenrain, Graz[a]	Mixed waste (MSW, Industrial Waste)	2016	X				X	X	X		X	Garcia Lopez et al. (2018)
Italy	Cagliari, Sardinia	Mainly MSW	1994	X					X			X	Cossu et al. (1996); Burlakovs et al. (2017)
Germany	Burghof Landfill	Mixed waste (MSW, C&D, sludge)	1993	X		X						X	Gäth and Nispel (2014); Goeschl (2010); Hölzle (2010); Cossu et al. (1996); Joseph et al. (2004)
	Sengenbühl, Bayern	MSW	1994									X	Gäth and Nispel (2014); Joseph et al. (2003)
	Schöneiche, Berlin	MSW	1995	X								X	Gäth and Nispel (2014); Bockreis and Jager (2009); Ortner et al. (2014)
	Schöneicher Plan	Mixed waste (MSW, industrial and hazardous waste, slag)	1995	X								X	Gäth and Nispel (2014); Bockreis and Jager (2009); Ortner et al. (2014)

	Baβlitz	–	–							X	Hogland (2002) ;Joseph et al. (2003)
	Döbeln-Hohenlauft	–	–							X	Hogland (2002); Joseph et al. (2003)
	Dresden	–	–							X	Hogland (2002); Joseph et al. (2003)
	Längenmoos, Bayern	–	2002	X							AWB (2002); Ortner et al. (2014)
	Rennerod	Mixed waste (MSW, C&D)	2006	X							Gäth and Nispel (2014); Hölzle (2010)
	Tiefenbach, Bayern	Mixed waste (MSW, C&D)	2008	X							Hölzle (2010)
	Hechingen	Mixed waste (MSW, C&D)	2009							X	Gäth and Nispel (2014)
	Holzg'wandenweg, Schwarzach	Mixed waste (MSW, C&D)	2009	X							Hölzle (2010)
	Jagerbergl, Tacherting, Bayern	Mixed waste (MSW, C&D)	2009	X							Hölzle (2010)
	Pitztalsgrund, Großwallstadt, Bayern	Mixed waste (MSW, C&D)	2009	X							GAB, 2010; Ortner et al. (2014)
	Am Heckenweiher, Feuchtwangen, Bayern	Mixed waste (MSW, C&D)	2009	X							Hölzle (2010); GAB, 2010; Ortner et al. (2014)
	Reiskirchen	Mixed waste (MSW, C&D, sludge)	2009							X	Gäth and Nispel (2014)
	Scheffau, Bayern	Mixed waste (MSW, C&D)	2009	X							GAB, 2010; Hölzle (2010)
	Walkmühle, Wunsiedel, Bayern	Mixed waste (MSW, C&D)	2009	X							Hölzle (2010)
Estonia	Kudjape[b]	Mixed waste (MSW, C&D)	2012–2013	X			X	X	X	X	X	Bhatnagar et al. (2013); Bhatnagar et al. (2017); Burlakovs et al. (2013); Hogland et al. (2014); Hogland et al. (2017)
	Torma[c]	MSW	–		X				X			Hogland et al. (2017)
	Laguja landfill	Mixed waste (MSW, industrial waste)	–	X								Ford et al. (2013); Kriipsalu et al. (2005)
Finland	Kuopio landfill	MSW	2012						X			Mönkäre et al. (2016)
	Lohja landfill	Mixed waste (MSW, C&D, soil)	2013						X			Mönkäre et al. (2016)
Netherlands	Apeldoorn	–	–	X								VAR (2000); Van Der Zee et al., 2004
	Arnhem	–	–							X		De Groot (2001); Van Der Zee et al. (2004)
	Born	–	–							X		De Visser (2002); Van Der Zee et al. (2004)
	Heiloo	–	–		X							De Visser (2001); Van Der Zee et al. (2004)
	Veenendaal	–	2001 [2 projects]				X					Geusebroek (2001); Burlakovs et al. (2017)
Sweden	Landskrona	Mainly MSW	1993								X	Rosendal (2009)
	Filborna	Mixed waste (MSW, C&D, industrial waste)	1994								X	Joseph et al. (2004); Rosendal (2009)
	Gladsax	Mixed waste (MSW, C&D)	1996						X		X	Hogland et al. (2004)
	Måsalycke landfill	Mainly MSW|	1996						X		X	Hogland et al. (2004)
	Strängnäs	Mixed waste (MSW, C&D)	2000–2004		X		X					Rosendal (2009)
	Högbytorp landfill	Mixed waste (MSW, industrial waste)	2014						X		X	Hogland et al. (2017); Jani et al. (2016)
	Vika landfill	Mixed waste (MSW, industrial waste)	–						X			Hogland et al. (2017)
Switzerland		Hazardous Waste	since 2007	X								

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Table 2 (*continued*)

Country	Project area	Types of waste	Period	Objectives			Recovery			Waste characterization	Urbanization	Studies	References
				Environmental Protection	Closure and post-closure	Lifetime extension	Soil	Energy	Recyclable materials				
	Kölliken Hazardous Waste Landfill												DIAS, 2016; Rosendal (2009); SMDK (2009); Ortner et al. (2014); SMDK, 2011
	Elbisgraben's Slag Landfil	Slag waste	2008						X				BAFU (2009); Ortner et al. (2014)

Initials: MSW – Municipal Solid Waste; C&D – Construction and Demolition Waste.
[a] These projects had several initial objectives. However, after the study, a large-scale project was not carried out.
[b] Not all the initial objectives of the project were met.
[c] Only the characterization of the waste was carried out.

dry water source was cleaned, which had a waste deposit underneath which was also removed. More than 50% of the recovered material was reused for backfilling at the landfill site and for recycling (metals and wood).

In Lebanon, there were two studies. The first was carried out in Beirut city from 2003 to 2005 (North and South, 2013). The Normandy Landfill Reclamation Project was part of the reconstruction and rehabilitation of the city, which began in the 1990s, after 15 years of the country civil conflict (Sadek and El-Fadel, 2000). This seashore dumpsite received several types of waste between 1975 and 1994. This project had difficult conditions due to the dumpsite characteristics, since approximately 50% of the volume was below sea level, reaching water depths between 18 and 20 m (North and South, 2013; Sadek and El-Fadel, 2000). The main objectives were to treat the dumpsite material (reusing the safe material) and to reclaim the land to market it (North and South, 2013). The second was in the Saida dumpsite, which had been in operation for more than thirty years, and it was administered by the municipality, receiving all kinds of waste (Gharib, 2017). The objectives were to solve the environmental and public health situation of the landfill and recover the land for a public park construction (UNDP, 2018). Construction material was also according to international standards (Gharib, 2017).

3.2. Asia

The Asian countries that have used this technique are India, Thailand, China, Taiwan, South Korea, Sri Lanka, and Pakistan. The oldest project in Asia was in India. It was carried out in Deonar city in 1989 and aimed to recover the fine material to commercialize as mixed fertilizer (Joseph et al., 2004). The other initiatives found in this country were applied between 1997 and 2013, and their main objective was the environmental protection of degraded areas (Hogland and Joseph, 2008; Joseph et al., 2003; Lechtenberg, 2008; Ranjan et al., 2014). This country has been a pioneer using a low-cost technique called "bio-mining" that employs biological treatments for the remediation of dumpsites. In this technique "*loosened layers of old waste are sprayed with composting bio-cultures and then formed into conventional aerobic wind-rows above-ground, on-site. The waste is thus sterilized, stabilized and its volume is minimized*" (Patel, 2016). As evidenced in Patel (2016), this technology with LM allow to protect degraded areas by removing gases and leachate from the landfill, recovering a large amount of excavated material in a short time.

The Chinese project encountered was from 1997 in the San Lin Transfer Site (Howlett, 1997). This transfer site was established in the 1970s as an intermediate area between Shanghai and the landfill sites. Although the site did not work anymore as a transfer station since the late 1980s, there were two large mounds of waste estimating a total volume of 1,000,000 m^3. The ships that worked in the dock near this station continued to dispose waste yonder, which explains around 30 waste pickers (WPs) working in the area. Lin Transfer was a good opportunity to evaluate the LM technique. The excavated residues were used as: the soil fraction and biodegraded organics as compost in a horticulture program and the inorganics were used for energy recovery. The non-combustible residual was sent to a landfill (Joseph et al., 2004).

Taipei had the two projects of Taiwan. The first was made at Neihu landfill, between 2006 and 2013, which was reclaimed as a park posteriorly. The main purpose consisted in the environmental rehabilitation of the closed riverside land and the river. The excavated waste was used as construction material, for energy production in nearby municipal incinerators and a small incombustible part was sent to a landfill (Weng et al., 2015). The second was in 2013; the Shanchuku Sanitary Landfill was also transformed in a park (AECOM, 2015; Betasolo et al., 2017).

3.3. North America

Between 1950 and 1980, two technologies were developed in the United States of America (USA). The first one refers to the systems of modular use to process mixed waste in final disposal sites or transfer stations; and the second, concerns with the technical feasibility evaluation of composting solid waste in landfills (Joseph et al., 2004).

The first initiative in the USA was in Naples, Florida (1986–1992), and was focused on the reduction of pollution, the recovery of materials, the reduction of post-clause costs and the landfill lifetime extension (Joseph et al., 2004). According to Von Stein and Savage (1993), only the soil portion from the recovered materials had a degree of purity that allowed reusing. Other materials conditions, such as iron and plastics, were unfitted for the market without secondary operations. Based on this experience, the State of New York, anticipating the closure of many landfills, evaluated the technical and economic viability of LM (Guerriero, 1996). In Edinburg landfill, the objective was not only to determine the recovery materials procedures but their reintroduction to the market (Strange, 2010). The results proved feasible regarding landfills recovery. The next evaluation was in Tonawanda, Hague, Chester, Horicon, Moriah, and Colonie landfills. The results reassured that studies are necessary before large-scale project (Guerriero, 1996).

In the 1990s, there were many projects in the USA focused on landfill lifetime extension or fully recovering (IWCS, 2009; Joseph et al., 2004; Nelson, 1995). According to Krook et al. (2012), the use of LM was related to the 1993 norm about non-hazardous solid waste management,[1] which established criteria for waste final disposal and strict requirements for closing a landfill (Spencer, 1990; Richard et al., 1996a,b; Krook et al. (2012)). The norm precipitated the closure of several landfills and LM projects focused on landfill lifetime extension and environmental remediation. After this boom, LM proposals decreased due to the economic situation and the lower demand for landfills as recycling and waste treatment technologies were improved (Krook et al., 2012).

The Canadian projects focused on environmental protection and recovery of materials (Dewaele and Brunet, 2016; Nelson, 1995).

3.4. Europe

The first LM European experience was in the United Kingdom in the 1980s. In order to allow urban development on Chatham Dockyard estate, waste had to be removed out of the old dockyard tip (Atkinson, 2010; Ford et al., 2013). In 1990, Austrian LM project in Donaupark (Austria) used a pioneer aerobization biological treatment (ABT) to recover higher quality material (Spillmann, 2001). The same treatment was applied to other projects in Austria (Garcia Lopez et al., 2018; Spillmann, 2001) and in UAE as aforementioned (Goeschl, 2006).

During the 1990s several pilot studies were carried out in Europe: Italy (1994), Germany (between 1993 and 1996) and Switzerland (between 1993 and 1996) (Burlakovs et al., 2017; Hogland, 2002; Joseph et al., 2004; Ortner et al., 2014; Rosendal, 2009).

The Council Directive 1999/31/EC of 26 April 1999 on waste landfilling changed the situation regarding the final disposal of waste both in the EU Member States and in the countries intended to be Members (Hogland, 2002). This directive established technical and operational criteria to prevent and reduce the negative environmental impacts of sanitary landfills, specifically, the pollution of surface water, groundwater, soil and air, greenhouse effect, and human health (EC, 1999). In general, this norm promoted LM projects in Europe (Ortner et al., 2014). Thus, after the enactment of this norm, a large number of projects focused on the environmental protection of degraded areas were carried out in Austria, Germany, Estonia, Sweden, Switzerland, United Kingdom, and others (Bhatnagar et al., 2013; Ford et al., 2013; Garcia Lopez et al., 2018); Hogland et al. (2017); Hölzle (2010); Jani et al. (2016); Ortner et al. (2014); Rosendal (2009).

In 2006, the LM projects Tiefenbach, Jagerberg, Pitztal Grund, Am Heckweiher, Scheffau, and Walkmühle, in the Bayern state (Germany), were implemented after the law that modified waste management and soil protection established a government fund to carry out landfill's rehabilitation with a focus on water environmental protection (Hölzle, 2010; Ortner et al., 2014).

Complied to EU Directive, several countries adopted LM projects for small and medium landfills remediation (Bhatnagar et al., 2013; Burlakovs et al., 2017; Hogland et al., 2017; Jani et al., 2016; Mönkäre et al., 2016; Ortner et al., 2014; Rosendal, 2009). Thus, in Europe, the interest has generally been the environmental protection of degraded areas.

The LM projects analyzed included company reports that might unrevealed the original purposes and the degree of compliance. Nevertheless, the majority fulfill their objectives. The exceptions, listed in Table 2, either declined to turn into large-scale or established ambitious objectives.

Several authors agree that the first step to a LM project is the identification of disposed waste (Bhatnagar et al., 2017; Dubey et al., 2016; Hogland et al., 2004; Ortner et al., 2014; Salerni (1995); Hogland et al. (2017) and Garcia Lopez et al. (2018)). Table 2 presents the main type of waste for each project. Most of the projects were executed in MSW landfills (48%), while the remaining in sites with mixed waste (35%), and industrial and/or hazardous waste (5%). No information was found about 12% of the projects. These results prove that it is possible to execute LM in any type of landfill; but, as the Kölliken project demonstrates, the costs, infrastructure, and required care are different depending on the type of excavated waste (SMDK, 2011).

4. Discussion

More than 40% of the projects analyzed were in Europe, followed by North America (31%), Asia (21%) and the Middle East (4%). Noticeable, no LM projects were found in Latin America, Africa and Australia. Figs. 1 and 2 compiled the results from this study. Fig. 1 shows the radar diagrams of the categories trend in each region where LM was developed, highlighting the percentage frequency distribution of each category. From this figure, it can be compared the approaches given by each region to the use of this technology. Mostly, the projects were a consequence of the enactment of more restrictive public policies on solid waste management or by government initiatives. In USA, the focus was given to the extension of useful life and environmental protection due to more stringent policies for the final disposal of waste in sanitary landfills (Krook et al., 2012). In Europe, most of the projects were focused on the environmental protection of groundwater, being motivated by the EU Landfill directive in 1999 (Hölzle, 2010; Ortner et al., 2014). The cases presented in the Middle East focused on the urbanization of the old landfills were the result of the local situation and government initiatives, due to civil wars or accelerated urbanization in their territories (Goeschl, 2006; Lechtenberg, 2008; UNDP, 2018). In Asia, most of the projects are in India, which has many dumpsites, and an attempt to reverse their environmental impacts. Several Asian LM projects were motivated by government organizations (AECOM, 2015; Patel, 2016; Ranjan et al., 2014; Weng et al., 2015).

[1] Resource Conservation and Recovery Act (RCRA) - Subtitle D.

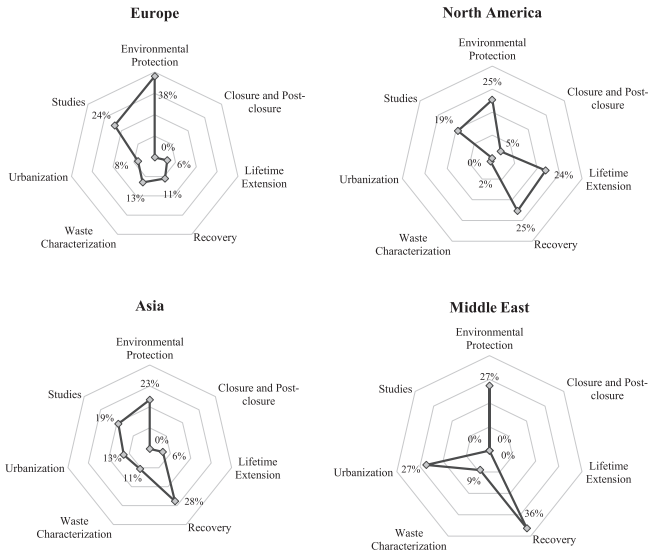

Fig. 1. Main Landfill Mining goals according to each region.

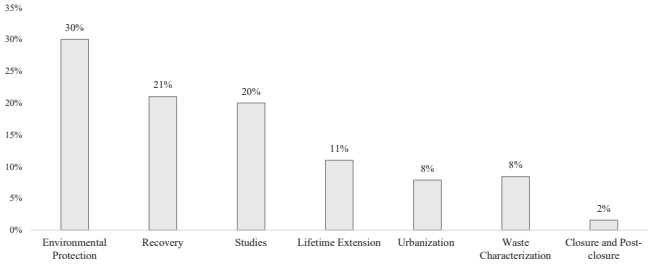

Fig. 2. Percentage distribution of objective categories for worldwide LM projects.

Fig. 2 presents the categories of objectives for LM projects and their percentage distribution. The importance given to *environmental protection topic* (30%) is evident, and it is consistent with Fig. 1, where this goal was the most representative in almost all regions. The projects with this focus involved measurements about groundwater protection, risk mitigation for surface water, hazard control in terms of landfill stability, control on landfill emissions, and extraction of hazardous waste, reducing negative impacts on the environment, especially, on water sources, soil, air and mitigation of climate change. Even when the main motivation is not environmental protection, all large-scale projects that implement this technique have positive impacts on the environment (Burlakovs et al., 2017; Joseph et al., 2004).

In second place is the *recovery of excavated waste* category (21%). This includes three subcategories: recovery of soil, energy recovery and recyclable materials recovery. Among all projects with the objective of recovery, the soil recovery is the most representative subcategory (52%). In second and third place are the recovery of recyclables and energy, reaching 28% and 20%, respectively.

Regarding soil recovery, the production of compost and fertilizers for plantations and its use as covering material to new landfills predominated in almost all projects that applied this subcategory. The second subcategory was recycling to obtain secondary raw materials, which depends on the composition and quality of the recovered material. LM projects with this purpose should consider the cost and time for separation and recycling of materials (IWCS, 2009). A comparison between the projects shows that the elements with the highest reuse rate are metals, construction materials and wood. Lastly, the fractions with low-quality conditions that cannot be transformed into secondary raw material are used in co-incineration plants or as refuse derived fuel (RDF). Thus, LM fits into the current transition that countries worldwide are making to the circular economy, by preserving natural resources and reducing the amount of waste generated and disposed of in landfills.

Third place is occupied by the *study* category, which accounted for 20% of the projects. In this case, there were not only pilot studies and demonstration projects, but also large-scale projects focused on assessment of technical and economic feasibility, materials recovery feasibility, landfill reclamation procedures, design parameters and infrastructure, and technological routes for recovery of excavated waste. In Europe, there was the largest number of these studies (45%), mainly in Germany and Sweden, followed by North America and Asia with 32% and 23%, respectively. In Asia, these studies were focused on the evaluation of recovering useful materials (Hogland and Joseph, 2008; Joseph et al., 2004; Prechthai et al., 2006). Concerning the waste characterization category, it scored 8% of the total projects, of which more than a half are also in the studies category. Of the remaining percentage, 25% was part of large-scale projects, while 19% did not present more objectives for the LM project.

Landfill lifetime-extension and *closure-and-post-closure* categories accounted for 11% and 2% of the projects, respectively; 72% of the projects classified within these two categories were found in USA (IWCS, 2009; Joseph et al., 2004; Nelson, 1995). The causes to develop LM projects with these objectives were the strict requirements for landfill Post-Closure Care as well as the difficulty of finding new land for the final disposal of waste.

Closing-and-post-closure is one of the most important criteria concerning sustainable practices for a sanitary landfill. The minimum period necessary for post-closure care depends on the regulations of each country, in the case of the USA; it is 30 years (Townsend et al., 2015). Regarding LM projects with this objective, all cases belong to this country, which were motivated by rigorous regulations, as aforementioned. When comparing the trend of this country with other regions, it becomes evident that LM projects depend on the requirements of each territory. In the USA, LM projects were carried out in sanitary landfills, while in other parts of the world, in dumpsites (as in the case of Asia and the Middle East) or in old landfills with many types of waste (Europe). In these regions, it is more important to implement LM to remedy the problems arising from inadequate final disposal sites.

Lastly, the urbanization category accounted for 8% of the projects. In the Middle East, 75% of the cases urbanized their old dumpsites as part of the decontamination of large cities. All these cases benefited from the potential of excavated waste (Gharib, 2017; Goeschl, 2006; Lechtenberg, 2008; North and South, 2013; UNDP, 2018). More than 50% of the projects used the land for construction of recreational areas (Betasolo et al., 2017; Burlakovs et al., 2017; Gharib, 2017; Patel, 2016; Twyford, 2008; UNDP, 2018; Weng et al., 2015). Other projects used the land for construction of residential and industrial areas (Ford et al., 2013; Goeschl, 2006). In general, LM projects whose final purpose was the urbanization of old landfills contribute to relieving public health problems of nearby community and to valorization of the surrounding lands.

In developing countries dominate inadequate disposal sites, which are close to large cities (Singh et al., 2009). Moreover, it is a known issue, that WPs in these disposal sites work informally recovering and selling the valuable materials to guarantee their subsistence (Medina, 2005; ISWA, 2016). In this sense, these sites impact on other problems such as unsafe working conditions and social inequality in these regions. Thus, finding measures that

mitigate these serious consequences is relevant and LM is presented as a strategic tool to give solutions to these problems.

4.1. Correlation of LM and the signed agreements

Most of the analyzed projects employed this technique for environmental protection and recovery of excavated waste. However, LM brings other economic and social benefits that whenever incorporated into the waste management sector, can promote its potential by assisting in the feasibility of SD, addressing both the Agenda 2030 goals and the Paris Agreement. The use of LM as a strategic tool is in line with at least 11 of the 17 SDGs of the Agenda 2030 for SD (See Table 3). LM benefits also contribute to the Paris Agreement fulfillment, which "*aims to strengthen the global response to the threat of climate change, in the context of SD and efforts to eradicate poverty*" (UN, 2015b). Its cross-cutting effect and its impact on several SDGs can influence the importance of its implementation in many countries. Table 3 presents the relationship between the SDGs and some of their specific targets with the benefits obtained through LM.

LM contributes to the fulfillment of SDG 3 (health and well-being) and SDG 6 (clean water and sanitation) by promoting the protection, not only of soil but also water sources, mainly groundwater, when is used for the extraction of hazardous waste and other types of waste that are disposed of on dumpsites or uncontrolled landfills. The contamination of groundwater is generated by the leachate of hazardous waste and is the most severe environmental consequence of these disposal sites, as it has been recognized since the 1980s by several authors (Singh et al., 2009, 2010; Reinhart, 1993).

SDG 13 (action for climate), the Paris Agreement objectives and the SDG 7 (Affordable and clean energy) are fulfilled by being positively influenced by the reduction of greenhouse gases (GHG) when the extracted waste from landfills is used for energy production. Psomopoulos et al. (2009) highlight that "*on average, combusting 1 metric tonne of MSW in a modern waste-to-energy (WTE) power plant generates a net of* 600 kWh *of electricity, thus avoiding mining a 1/4 tonne of high-quality US coal or importing one barrel of oil*". In the case of excavated waste, it is difficult to estimate its calorific values due to the decomposition process happening inside the landfills. However, according to Franke et al. (2010), research carried out in old landfills have shown that even after many years of disuse, high calorific values are preserved in the excavated residues present. Therefore, the use of solid waste recovered from old landfills or dumpsites through the LM (as WTE), can substitute fossil fuels and contribute with the reduction of massive GHG emissions (Wang et al., 2017).

Additionally, landfills and dumpsites are a reservoir of methane, which is a potent GHG (Hoornweg and Bhada-Tata, 2012). According to the USEPA (2006), methane contained in landfills worldwide represents 12% of total global methane emissions. Hence, LM applied for landfill recovery or for the use of buried waste contributes to reduce emissions from the waste management sector, and so it also contributes to the fulfillment of SDG 13 (action for climate) and the Paris Agreement.

The fulfillment of SDG 11 (sustainable cities and communities) is reinforced due to the reduction of environmental impact related to the waste management and the recovery of degraded areas for urbanization. The urbanization of old waste disposal sites in cities is crucial because of the accelerated growth of urban areas, which increases the demand for construction land; especially in low- and low-middle income countries where the rates of urbanization will be the fastest growing (UN, 2018). According to the United Nations (2018), the proportion of world's population living in urban areas is projected to grow from 55% in 2018 to 68% by 2050. On the other hand, due to uncontrolled urbanization processes in developing countries, those dumpsites that were once far from urban centers are now surrounded by new constructions, which are affected by the proximity to inadequate disposal sites. The recovery of degraded areas through LM prevents public health problems of nearby populations and contributes to the preservation of existing fauna and flora assisting, in this case, to fulfillment of SDG 15 (life of terrestrial ecosystems) as well.

In addition to the direct environmental and economic benefits discussed previously, LM treated as a strategic management tool promotes the socio-economic inclusion of informal miners, referring to current WPs working in dumpsites and controlled-landfills that could go through a formalization process. In this sense, there are two possibilities of action in favor of these vulnerable groups. The first, through their incorporation as miners in the recovery processes of valuable materials, and the second by their social inclusion within the waste management systems.

The work of the WPs inside dumpsites is one of the most dangerous jobs in terms of occupational health (Wilson et al., 2006). In this sense, their incorporation as miners for the recovery of valuable materials from these landfills should guarantee the sanitary conditions for the protection of these workers. These considerations should be highlighted within public policies that will adopt LM as a tool for social inclusion. Although many studies conclude that occupational health impacts of LM projects are minimal (Krook et al., 2012), it is necessary for the authorities to demand occupational safety and health programs that contemplate the possible risks associated with this activity (Cossu et al., 1996; Krook et al., 2012).

Moreover, there are millions of informal WPs working in dumpsites around the world, so the most significant social impact of the closure of these disposal sites is linked to the survival of these workers. Thus, when closing dumpsites, it is necessary to begin a process of social inclusion of WPs within the waste management systems, which is a step towards inclusive and sustainable economic growth (ISWA, 2016). According to Aparcana (2017) there are three current approaches for the inclusion and formalization of WPs in these systems: organizing informal waste-workers in associations and cooperatives, organizing recyclers in CBOs (Community Based Organizations) or MSEs (Micro- and Small Enterprises) and adopting informal waste-workers as workers for the formal waste management sector. Then, the formalization improves the work conditions and incomes of this vulnerable population, promoting the fulfillment of SDG 1 (end of poverty). This is also related to SDG 8, which proposes goals for decent work, and SDG 10 in terms of reducing inequalities.

Based on that information, LM is a technological resource that, when incorporated into waste management public policies as a strategic tool, adds social, environmental and economic benefits to the society, thus leading companies towards SD and the climate change mitigation.

5. Conclusion

This article considered the evolution of LM projects implemented since 1953 in four regions of the world for discussing the role of this technology and its influence in compliance with the Agenda 2030. For most of the cases, there is no information available that allows knowing its degree of compliance. Evidently, projects fitted the stated objectives, except for some indicated cases.

LM objectives depend on the specific demands of each region and its waste management policies. The initiative for the implementation of LM projects is mainly from the public sector. Therefore, it decides if a studio is transformed into a large-scale project or

Table 3
Relationship between landfill mining and sustainable development goals.

Sustainable Development Goal (SDG)	Specific Target	LM Benefit	LM Objective
SDG 1: No poverty	1.1. Eradicate extreme poverty for all people everywhere. 1.2. Reduce at least by half the proportion of men, women and children of all ages living in poverty. 1.4. Ensure that all men and women the poor and the vulnerable, have equal rights to economic resources and financial services, including microfinance. 1.5. Build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to economic, social and environmental shocks and disasters. 1. B. Create sound policy frameworks at the national, regional and international levels, based on pro-poor and gender-sensitive development strategies, to support accelerated investment in poverty eradication actions.	Inclusion of WPs	LM as a tool for social inclusion
SDG 3: Good health and well-being	3.2. End preventable deaths of newborns and children fewer than 5 years of age. 3.3. Combat water-borne diseases. 3.9. Reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination.	1. Surface water and groundwater protection 2.Reduction of environmental impact related to the waste management	Environmental Protection
SDG 6: Clean water and sanitation	6.3. Improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials.	Surface water and groundwater protection	
SDG 7: Affordable and clean energy	7.2. Increase substantially the share of renewable energy in the global energy mix.	Energy Recovery	Recovery of excavated waste
SDG 8: Decent work and economic growth	8.3. Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services. 8.5. Achieve full and productive employment and decent work for all women and men, and equal pay for work of equal value. 8.7. Take effective measures to eradicate forced labor, end modern slavery. 8.8. Protect labor rights and promote safe and secure working environments.	Inclusion of WPs	LM as a tool for social inclusion
SDG 10: Reduced Inequalities	10.1. Achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average. 10.2. Empower and promote the social, economic and political inclusion of all. 10.3. Ensure equal opportunity and reduce inequalities of outcome. 10.4. Adopt policies, especially fiscal, wage and social protection policies, and progressively achieve greater equality.	Inclusion of WPs	LM as a tool for social inclusion
SDG 11: Sustainable cities	11.1. Ensure access for all people to adequate, safe and affordable housing and basic services and upgrade slums. 11.3. Enhance inclusive and sustainable urbanization, integrated and sustainable human settlement planning and management in all countries. 11.6. Reduce the adverse per capita environmental impact of cities, special attention to waste management. 11.7. Provide universal access to safe, inclusive and accessible, green and public spaces. 11. A. Support positive economic, social and environmental links between urban, per-urban and rural areas by strengthening national and regional development planning.	Reduction of environmental impact related to the waste management Urbanization	Environmental Protection Urbanization
SDG 12: Responsible consumption and production	12.2. Achieve the sustainable management and efficient use of natural resources. 12.4. Achieve the environmentally sound management of chemicals and all wastes throughout their life cycle. 12.5. Reduce waste generation.	Recyclable materials recovery	Recovery of excavated waste
SDG 13: Climate action	13.1. Strengthen resilience and adaptive capacity to climate-related hazards in all countries. 13.2. Integrate climate change measures into national policies and planning. 13. B. Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing States.	Landfill emissions Energy Recovery	Environmental Protection Recovery of excavated waste
SDG 14: Life below water	14.1. Prevent and significantly reduce marine pollution of all kinds.	Risk mitigation for surface water	Environmental Protection
SDG 15: Life on land	15.1. Ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services. 15.2. Take urgent and significant action to reduce the degradation of natural habitats.	Soil recovery Urbanization	Recovery of excavated waste Urbanization

Source of SDGs and targets: UN, 2015a. The targets are presented in a summarized form.

if, on the contrary, it is not feasible according to local needs and budget. As evidenced in the different countries that carried out these projects, their advantages not only promote the adequate waste management but also include many other social and economic benefits. This research presented these benefits which could help policy-makers and waste management professionals to develop this kind of projects in their countries in order to implement sustainable technologies. It should be noted that regardless of whether the project considers environmental protection as a driver, positive outcomes will be obtained in this aspect in big-scale projects.

As it has been demonstrated, LM as a strategic tool can be established in public policies to fulfill at least 11 of the 17 SDGs. To demonstrate, the article discussed three objectives categories (environmental protection, recovery of excavated waste and urbanization) and its repercussion in the fulfillment of the SDGs. To comply with specific SDGs, the economic, social and environmental situation of the territory must be studied before implementing this technology. Its proper use will ensure significant contributions towards the achievement of SD and mitigation of climate change.

Another aspect to be added is the one associated with the closing-and-post-closure of landfills. The authors also consider the use of LM successful in regions whose main technology is a sanitary landfill for the final disposal of waste, considering the increasingly rigorous criteria imposed by regulations and the effects on the environment of these sites, even after several years of disuse.

Finally, the authors propose the use of Landfill Mining as a tool for social inclusion for compliance with SDGs related to social development. In this last approach, according to the characteristics of Latin America and other countries in the Southern Hemisphere, this tool can bring social benefits to the social inclusion of WPs.

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Abbreviations

(SD): Sustainable Development
(SDGs): Sustainable Development Goals
(LM): Landfill Mining
(UAE): United Arab Emirates
(USA): United States of America
(RDF): Refuse Derived Fuel
(MSW): Municipal solid waste
(C&D): Construction and Demolition Waste
(ABT): Aerobization Biological Treatment
(WTE): Waste-to-energy
(GHG): Greenhouse gases
CBOs: (Community Based Organizations)
MSEs: (Micro and Small Enterprises)
(WPs): Waste Pickers